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Biologically-Inspired, Anisotropic Flexible Wing for Optimal Flapping Flight

Luis Bernal, Wei Shyy, Carlos Cesnik, Peretz Friedmann, Peter Ifju, Rick Lind, Larry Ukeiley, Sean Humbert
University of Michigan

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University of Michigan, 3003 South State St., Ann Arbor, MI 48109-1273
University of Florida, 339 Weil Hall, Gainesville, FL 32611-6550
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14. ABSTRACT
A multidisciplinary program involving collaboration between eight researches at three universities to address fundamental aspects of flapping wing micro aerial vehicles (MAV) is described. The overall goal of the program was to develop the fundamental scientific foundation necessary to enable the design of agile, autonomous flapping-wing MAVs for operation in an urban environment. Significant accomplishments include: a) Developed and validated high- and low-fidelity computational tools for analysis and design of flapping wing MAVs; b) Developed and used measurement techniques to determine the relation between wing kinematics, geometry, and anisotropic structural flexibility; c) Conducted coordinated experimental and computational modeling to determine the roles of aerodynamic loading, wing inertia, and structural flexibility and elasticity; and d) Developed surrogate tools for flapping wing MAV design and optimization. Detailed research accomplishments have been documented in 83 archival publications, 11 Ph.D. Dissertations and 5 Master Thesis. Several archival publications are in collaboration with colleagues at AFRL.

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University of Michigan
Principal Investigator: Luis P. Bernal
Department of Aerospace Engineering,
The University of Michigan
3048 FXB, 1320 Beal Avenue
Ann Arbor, MI 48109
Phone: (734) 764-3396
Fax: (734)763-0578
lpb@umich.edu

Co-Principal Investigators:
Carlos Cesnik and Peretz Friedmann
Department of Aerospace Engineering, University of Michigan

Wei Shyy
Hong Kong University of Science and Technology, Kowloon, Hong Kong

Peter Ifju, Rick Lind, and Lawrence Ukeiley
Department of Mechanical and Aerospace Engineering, University of Florida

Sean Humbert
Department of Aerospace Engineering, University of Maryland

Contents

1. Summary

A multidisciplinary program involving collaboration between eight researches at three universities to address fundamental aspects of flapping wing micro aerial vehicles (MAV) is described. The overall goal of the program was to develop the fundamental scientific foundation necessary to enable the design of agile, autonomous flapping-wing MAVs for operation in an urban environment. To focus the research a notional flapping wing MAV with parameters similar to several biological systems like the bumblebee, hawkmoth, and hummingbird was identified and used as the basis for systematic studies of the flow physics, structural dynamics and flight mechanics. Specific research objectives include collaborations in the following research areas:

1. The flow physics of biology-inspired mechanisms that simultaneously provide lift and thrust, to enable hover, and minimize power consumption;
2. The interactions of unsteady aerodynamic loading with flexible structures;
3. Flexible, light-weight, multifunctional materials and structures for large displacement and suitable for actuators and sensors;
4. Gust-tolerant biology-inspired flight control methodologies incorporating novel sensors and wing structural property tailoring;
5. Integration of theoretical, numerical and experimental analysis techniques;
6. Power requirements, packaging and integration issues for flapping wing technologies relevant to MAV urban operations.

Significant accomplishments include:

a) Developed and validated high- and low-fidelity computational tools necessary for understanding and prediction of the coupled fluid and structural dynamics in unsteady, low Reynolds number flows;

b) Developed and implemented measurement techniques to probe the interplay between wing kinematics (including frequency, stroke amplitude, and angle-of-attack variations), geometry, and anisotropic structural flexibility;

c) Conducted coordinated experimental and computational modeling in vacuum chamber, wind tunnel, and water channel to separate the key roles of aerodynamic loading, wing inertia, and structural flexibility and elasticity;

d) Developed surrogate tools for flapping wing MAV design and optimization.

Detailed research accomplishments have been documented in 83 archival publications, 11 Ph.D. Dissertations and 5 Master Thesis. Several archival publications are in collaboration with colleagues at the Air Force Research Laboratory, Wright-Patterson Air Force Base.

2. Introduction

This report describes a multidisciplinary program involving collaboration between eight researches at three universities to address fundamental scientific aspects of bio-inspired flapping wing MAVs. In addition to the co-principal investigators approximate 40 students and post-doctoral fellows participated in the research. Detailed descriptions of the many research projects and scientific contributions can be found in the 83 archival publications, 5 Master Thesis and 11 Ph.D. Dissertations listed in Appendices A and B. Another feature of the program was collaboration with Drs. Michael Ol, Ray Gordnier and Miguel Visbal of the Air Force Research Laboratory, Wright-Patterson AFB, which resulted in 19 co-authored archival publications also listed in appendix A. In this report we refrain from discussing technical details of the different research projects which are readily available in the above mentioned publications, and focus instead on the research motivation and the 6 research areas that were identified in the proposal. We highlight the research contributions in these areas to provide context for the many research publications, and conclude with recommendations for future research.

Micro Air Vehicles (MAVs) have the potential to revolutionize DoD's 21st century combat capability. To meet the evolving threat, MAVs must have the ability to fly in urban settings, tunnels and caves, maintain forward and hovering flight, maneuver in constrained environments, and "perch" until needed. Due to the MAVs' small size, flight regime, and modes of operation, significant scientific advancement is needed to create this revolutionary capability. Insufficient knowledge, predictive capabilities, and experimental data exist regarding the fundamental unsteady aerodynamics of low Reynolds number flyers, and the associated fluid-structure-control interactions, flight mechanics, guidance and control.

In principle, one might like to first understand a biological system, then abstracting certain properties and applying them to MAV design. However, scaling of both fluid dynamics and structural dynamics between smaller natural flyer and practical flying hardware/lab experiment (larger dimension) is not well-understood. Furthermore, it is desirable to make best use of engineering advancements in materials, actuation, kinematics, and experimental and simulation tools to take advantage of the insight learned from natural flyers, while developing suitable guidelines for engineered MAV design.

Research in biological flapping wing systems provide considerable insight in the flow physics, structural mechanics and flight mechanics applicable to engineered flapping wing MAVs. However fundamental questions remain that are the subjects of the present research. These include: optimum flapping kinematics, fluid physics and lift enhancement mechanisms, gust response mechanisms, theoretical aerodynamic modeling and relevance of quasi-steady models, laminar-turbulent transition in highly unsteady flapping wings, fluid-structure interactions and the effect of anisotropic structural properties, sensing of flight environment and control of flapping wings. These questions motivated the main research areas of the research:

1. The flow physics of biology-inspired mechanisms that simultaneously provide lift and thrust, to enable hover, and minimize power consumption;
2. The interactions of unsteady aerodynamic loading with flexible structures;
3. Flexible, light-weight, multifunctional materials and structures for large displacement and suitable for actuators and sensors;
4. Gust-tolerant biology-inspired flight control methodologies incorporating novel sensors and wing structural property tailoring;
5. Integration of theoretical, numerical and experimental analysis techniques;
6. Power requirements, packaging and integration issues for flapping wing technologies relevant to MAV urban operations.

In what follows the main accomplishments of the research program are highlighted. The accomplishments are grouped according to these research areas.

3. Research Accomplishments

In this section the main research contributions are highlighted. For each contribution relevant dissertation and archival publications listed in Appendices A and B, respectively, are referenced by the corresponding number. The reader is referred to those publications for detailed accounts of the research.

3.1. The flow physics of biology-inspired mechanisms that simultaneously provide lift and thrust, to enable hover, and minimize power consumption.

3.1.1 Flow Physics of Pitching and Plunging Rigid Airfoils

Experimental studies of rigid wings undergoing pitching and plunging kinematics were conducted with SD7003 and flat plate airfoils to determine the scaling of lift and thrust coefficients as a function reduced frequency and motion amplitude for fixed effective angle of attack time history. The research focus was on the formation and dynamics of Leading and Trailing Edge Vortices (LEV and TEV) and their relation to aerodynamic force generation. It was found that LEV and TEV topology scales primarily with reduced frequency; while lift and thrust coefficients scale primarily with Strouhal number.

Dissertations (Appendix A): 4, 7, 11

Publications (Appendix B): 15, 27, 28, 30, 44, 45, 46, 48, 49, 50, 62

3.1.2 Flow physics of bio-inspired hover kinematics

The flow physics of bio-inspired hover kinematics of airfoils and wings in pitch-plunge and flapping was investigated experimentally using direct force measurement and PIV. Two bio-inspired and a sinusoidal kinematic were investigated. Thrust, lift and propulsion efficiency (figure of merit) were experimentally determined. PIV and flow visualization techniques are also being used to quantify vortex topology and its relation to force generation and propulsion efficiency.

Dissertations (Appendix A): 15

Publications (Appendix B): 75

3.1.3 PIV force measurements

Methodologies that use Particle Image Velocimetry measurements around membrane wings have been developed and refined to calculate a thrust in a hovering environment. This analysis has been used to show that the membrane material properties can be used to alter the spanwise twist profile and hence the location of the maximum force generation. Additionally the work has demonstrated the benefit of a constant velocity wing motion versus a purely sinusoidal motion. PIV based force measurements were also used to measure forces on a rapidly pitching flap plate

Dissertations (Appendix A): 7, 13

Publications (Appendix B): 57, 77

3.1.4 Aerodynamics of perching

The aerodynamic of perching maneuvers has been investigated. The effect of pitch rate on force and flow development has been measured for different pivot axis locations and pitch amplitude. LEV formation and detachment was determined using PIV. At low reduced pitch rate the flow is quasi-steady. At high reduced pitch rate significant rotation rate have been measure. Leading edge pivot produces much higher force that trailing edge pivot. Also at high pitch rates the flow evolution is more two-dimensional.

Dissertations (Appendix A): 7

Publications (Appendix B): 57, 59, 61, 66, 73, 79

3.2. Interactions of unsteady aerodynamic loading with flexible structures

3.2.1 multi-fidelity computational modeling of flapping wing aerodynamics and aeroelasticity

The multi-fidelity computational approach was developed and has been applied to flapping wing aerodynamics and aeroelasticity. Highlights of the research results are:

- Variation of the Reynolds number leads to a change in the LEV and spanwise flow structures, which impacts the aerodynamic force generation,
- Interaction between the TiV and the LEV enhances lift without increasing power requirements for delayed rotation kinematics with high angle of attack,
- Chordwise flexibility in forward flight can adjust its projected area normal to its flight path via shape deformation, redistributing thrust and lift,
- Spanwise flexibility in forward flight results in spanwise shape deformation leading to a phase shift between the wing tip and the root as well as varied effective angle of attach distribution and enhanced thrust generation

Dissertations (Appendix A): 1

Publications (Appendix B): 3, 6, 16, 21, 24, 29, 38, 40, 51

3.2.2 Experimental studies on pitching-plunging and flapping flexible wings

Experimental studies on the effect of flexibility on a pitching-plunging and flapping elliptical wing was conducted. Experiments were conducted in a water channel facility and in the wind tunnel. Highlights of the results in the water channel include:

- Flexibility effects are found for $\Pi_1 < 200$
- Increased effective angle of attack outboard
- Phase lag of maximum affective angle of attack compared to a rigid wing
- Spanwise flow in the vortex core
- Flow topology: LEV vortex strength increases outboard due to increased effective angle of attack

Dissertations (Appendix A): 8

Publications (Appendix B): 23, 43, 51, 63, 68, 72

3.2.3 Nonlinear aeroelastic model suitable for flexible insect-like flapping wings in hover

A nonlinear aeroelastic model suitable for flexible insect-like flapping wings in hover was develped. The aeroelastic model is obtained by coupling a nonlinear structural dynamic model based on MARC, with a potential flow based approximate aerodynamic model that consists of leading edge vortices and a wake model. The aeroelastic response is obtained using an updated Lagrangian method. The paper describes validation studies conducted on the structural dynamic model, aerodynamic comparisons, and aeroelastic studies conducted on isotropic and anisotropic Zimmerman wings. The results demonstrate the suitability of MARC for modeling anisotropic wings undergoing insect-like wing kinematics. For the aeroelastic cases considered, the approximate model shows acceptable agreement with CFD based and experimental results. The approximate model captured several important trends correctly.

Dissertations (Appendix A): 6

Publications (Appendix B): 31, 36, 41, 53, 82, 83

3.2.4 Nonlinear aeroelastic model suitable for flexible flapping wings in forward flight.

Aerodynamic and aeroelastic studies for flapping wings have been conducted using an aeroelastic model that combines a nonlinear structural dynamic model with an approximate aerodynamic model that incorporates leading edge vortices and a wake model. The principal contribution in this research is the extension of the earlier model, developed for hover, to forward flight. The effect of fluid viscosity is also incorporated in a partial manner. Results obtained for rigid airfoils operating at low Reynolds number indicate that incorporating the effect of viscosity improves correlation between the approximate model and CFD based results. For rigid wings in forward flight, the modified aerodynamic model shows acceptable agreement with CFD based results and it predicts the trends accurately. The trends obtained suggest that the forces generated by rigid wings, in both hover and forward flight, are insensitive to Reynolds number and scale with square of flapping frequency. The aeroelastic results presented indicate that lift enhancement due to flexibility that was demonstrated for hover is also present in forward flight. The choice of the `best' flexible configuration depends on the flapping frequency and wing kinematics.

Dissertations (Appendix A): 6

Publications (Appendix B): 65

3.3. Flexible, light-weight, multifunctional materials and structures for large displacement and suitable for actuators and sensors;

3.3.1 Synthetic, Flexible Small Flapping Wings

This research focuses on small synthetic wings which were biologically inspired by hummingbirds as they are comparable in size, shape, and flapping frequency. The focus was aimed at the average thrust production from a one degree of freedom flapping mechanism and the weight of each wing. The motivation arises with the final application of a standalone hovering device but brings to attention a question of whether or not to trust the current manufacturing process that consists of a carbon fiber hand lay-up method. The main objective of this work was to create a high-fidelity manufacturing process having repeatable and robust wings resulting in improved results where minute variations in average thrust production can be detected while in hover mode. To advance the possibilities and expand the testing envelope four distinct methods were proposed, the carbon fiber hand lay-up, a Teflon CNC milled mold, a milled plastic frame combined with a carbon fiber rod for support, and a unique attachment method with a 3M transfer tape.

Dissertations (Appendix A): 2,12, 16

Publications (Appendix B): 7, 20, 42, 54, 55

3.4. *Gust-tolerant biology-inspired flight control methodologies incorporating novel sensors and wing structural property tailoring*

3.4.1 Gust rejection in biological flight

The mechanisms of gust rejection in biological flight and understanding the aerodynamics of bio-inspired flapping wing kinematics have been investigated. Experiments were conducted to capture and digitize insect flight flight sequences. Insect's response to gust inputs has been documented. Theoretical, numerical and experimental analysis techniques have been developed.

Dissertations (Appendix A): 9, 14

Publications (Appendix B): 25, 32, 69, 81

3.4.2. Aeroservoelastic system identification and feedforward control of flexible flapping wings.

The dynamics of a flapping-wing vehicle are inherently aeroservoelastic since the interaction of aerodynamics and structural dynamics are critical to performance and will be altered by any control effectors. These dynamics have been shown to exhibit nonlinear behaviors in the time-frequency domain for a variety of wings. A model of the flapping wing as a function of each control effector may be formulated. These models capture the nonlinear behavior and are a basis from which to compute the deflection in response to any control command. In this research a model of the aeroservoelastic dynamics for a flexible flapping wing was developed. A feedforward controller is designed which determines the input flapping amplitude and flapping frequency considering some desired flapping profile and the experimental model. The values of the control effectors are input into the flapping model thereby tracking the deflections of a desired flapping profile.

Dissertations (Appendix A): 10

Publications (Appendix B): 47, 60

3.5. *Power requirements, packaging and integration issues for flapping wing technologies relevant to MAV urban operations.*

The multi-fidelity computational approach has been applied to determine power requirements of flapping wing MAVs at low Reynolds number

Experimental studies were conducted to measure propulsion efficiency of bio-inspired and other hover kinematics

Dissertations (Appendix A): 15

Publications (Appendix B): 72, 75, 80

4. Conclusion

The multidisciplinary research program on bio-inspired flexible wing for flapping flight provided an opportunity to develop unique computational and experimental capabilities to analyze the coupled flow dynamics, structural dynamics and flight mechanics of biological flight systems. These capabilities have enabled a large number of more focused projects to investigate relevant scientific issues. In closing we note some significant challenges that remain. On the computational side the complexity of the coupled fluid/structure problem lead to very long computational times and numerical difficulties at higher Reynolds number. Improved high-fidelity computational tools will continue to be important for researchers in this field. Low-fidelity models have been developed and used in this research and provide a useful tool for engineering analysis and optimization.

On the experimental characterization of flexible flapping there are many challenges which need to be resolved. Accurate measurement of wing deformation, particularly of thin membrane wings, is very challenging and better techniques are needed. Dynamic tare necessary for direct aerodynamic force measurement on flexible wings presents some difficult issues that are not fully resolved at this point. Also to characterize these flows 3-D flow field measurement techniques must be improved to investigate issues of laminar-turbulent transition and tip vortex effects in these flows.

Appendix A - Dissertations

PhD Dissertations

1. Satish K. Chimakurthi (2009) “A Computational Aeroelasticity Framework for Analyzing Flapping Wings,” Ph.D. Dissertation, University of Michigan. Co-Chairs: W. Shyy and C. Cesnik.
2. Y.-C. Cho (2010) “Low-Reynolds Number Adaptive Flow Control Using Dielectric Barrier Discharge Actuator” Ph.D. Dissertation, University of Michigan. Chair: W. Shyy.
3. Pin Wu, (2010) “Experimental Characterization, Design, Analysis And Optimization Of Flexible Flapping Wings For Micro Air Vehicles,” Ph.D. Dissertation, University of Florida, Chair: P. Ifju.
4. Chang-Kwon Kang (2011) “Aerodynamics, Scaling, and Performance of a Flexible Flapping Wing” Ph.D. Dissertation, University of Michigan. Chair: W. Shyy.
5. Patrick C. Trizila (2011) “Aerodynamics of Low Reynolds Number Rigid Flapping Wing Under Hover and Freestream Conditions,” Ph.D. Dissertation, University of Michigan. Chair: W. Shyy.
6. Abhijit Gogulapati (2011) “Nonlinear Approximate Aeroelastic Analysis of Flapping Wings in Hover and Forward Flight,” Ph.D. Dissertation, University of Michigan. Chair: P. Friedmann.
7. Yeon Sik Baik (2011) “Unsteady Force Generation and Vortex Dynamics of Pitching and Plunging Airfoils at Low Reynolds Number,” Ph.D. Dissertation, University of Michigan. Chair: L.P. Bernal.
8. Erik Sällström (2011) “Flow field of flexible flapping wings,” Ph.D. Dissertation, University of Florida. Chair: L. Ukeiley.
9. Imraan Faruque (2011) “Dipteran Insect Flight Dynamics Modeling, System Identification, and Control,” Ph.D. Dissertation, University of Maryland. Chair: S. Humbert.
10. Robert Love (2012) “An Experimentally-Based Procedure for Aeroservoelastic Model Identification and Control Synthesis for Morphing and Flapping Wings” Ph.D. Dissertation, University of Florida. Chair: R. Lind.
11. Adam Hart (2013) “Unsteady Fluid Dynamics Over a Low-Aspect-Ratio Pitching Plunging Flat Plate,” Ph.D. Dissertation, University of Florida. Chair: L. Ukeiley.

Master Theses

12. Justin McIntire, (2011) “Investigating Torsional Compliance Of Flapping Wings To Maximize Thrust Capability,” Master Thesis, University of Florida. Thesis Adviser: P. Ifju.
13. Diego Campos (2012) “Effects of Isotropic Flexibility on Wings Under a Plunging Motion,” Master Thesis, University of Florida. Thesis Adviser: L. Ukeiley
14. Nick Kostreski (2012) “A Comparative Study of Gust Mitigation Approaches in Insects.” Master Thesis, University of Maryland. Thesis Adviser: S. Humbert.
15. Ruben Vandenheede (2012) “Force Generation of Bio-Inspired Hover Kinematics,” Master Thesis, Delft University of Technology. Thesis Adviser: L. Bernal.
16. Jason Rue (2013) “Investigating Manufacturing Techniques, Testing, And Design To Enhance Confidence In Thrust Production For Synthetic Flexible Small Flapping Wings,” Master Thesis, University of Florida. Thesis Adviser: P. Ifju.

Appendix B - Publications

Books

1. Shyy, W., Aono, H., Kang, C.-K., and Liu, H. (authors), *An Introduction to Flapping Wing Aerodynamics*, Cambridge University Press, New York (2013)

Book Chapters

2. Stanford, B, Ifju, P., Albertani, R., and Shyy, W., "Fixed Membrane Wings for Micro Air Vehicles: Experimental Characterization, Numerical Modeling, and Tailoring," *Progress in Aerospace* Sciences, Vol. 44, (2008), pp. 258-294.

3. Shyy, W., Lian, Y., Chimakurthi, S.K., Tang, J., Cesnik, C.E.S., Stanford, B., and Ifju, P.G., "Flexible Wings and Fluid–Structure Interactions for Micro-Air Vehicles," Chapter 11, Flying Insects and Robots, Dario Floreano, Jean-Christophe Zufferey, Mandyam V. Srinivasan, and Charlie Ellington (Editors), pp. 143-157, Springer-Verlag, Berlin, Germany, (2009).

4. Shyy, W., Aono, H., and Liu, H., "Flapping Wing Aerodynamics," *Encyclopedia of Aerospace Engineering*, R. Blockley and W. Shyy (Editors), Wiley, Vol. 1, Chapter 17, (2010), pp. 231-243.

5. Liu, H., and Shyy, W., "Micro Air Vehicle-Motivated Aerodynamics," *Encyclopedia of Aerospace Engineering*, R. Blockley and W. Shyy (Editors), Wiley, Vol. 7, Chapter 346, (2010), pp. 4265-4277.

6. Shyy, W., Aono, H., Chimakurthi, S.K., Trizila, P., Kang, C.-K., Cesnik, C.E.S., and Liu, H., "Recent Progress in Flapping Wing Aerodynamics and Aeroelasticity," *Progress in Aerospace Sciences*, Vol. 46, (2010), pp. 284-327, doi: 10.1016/j.paerosci.2010.01.001.

7. Xie, Lunxu, Pin Wu, and Peter Ifju "Advanced Biologically-Inspired Flapping Wing Structure Development." In *Experimental and Applied Mechanics, Volume 6*, pp. 365-371. Springer New York, 2011.

8. Abate, G., and Shyy, W., "Bio-inspiration of Morphing for Micro Air Vehicles," in *Morphing Aerospace Vehicles and Structures*, J. Valasek (Ed.), pp. 41-53, Wiley, New York (2012).

Journal Publications

9. Shyy, W., and Liu, H., "Flapping Wings and Aerodynamic Lift: The Role of Leading-Edge Vortices," *AIAA Journal*, Vol. 45, (2007), pp. 2817-2819.

10. Stanford, B., Sytsma, M., Albertani, R., Viieru, D., Shyy, W., and Ifju, P., "Static Aeroelastic Model Validation of Membrane Micro Air Vehicle Wings," *AIAA Journal*, Vol. 45, (2007), pp. 2828-2837.

11. Tang, J., Viieru, D., and Shyy, W., "Effects of Reynolds Number and Flapping Kinematics on Hovering Aerodynamics," *AIAA Journal*, Vol. 46, (2008), pp. 967-976; also 45th AIAA Aerospace Sciences Meeting and Exhibit, 8-11 January 2007, Reno, Nevada, Paper No. AIAA 2007-129.

12. Shyy, W., Lian, Y., Tang, J., Liu, H., Trizila, P., Stanford, B., Bernal, L.P., Cesnik, C.E.S., Friedmann, P., and Ifju, P., “Computational Aerodynamics of Low Reynolds Number Plunging, Pitching and Flexible Wings for MAV Applications,” *Acta Mechanica Sinica*, Vol. 24, (2008), pp. 351-373, doi: 10.1007/s10409-008-0164-z; also, 46th AIAA Aerospace Sciences Meeting and Exhibit, 7-10 January 2008, Reno, Nevada, Paper No. AIAA 2008-523.

13. Aono, H., Shyy, W., and Liu, H. “Vortex Dynamics in Near Wake of a Hovering Hawkmoth,” *Acta Mechanica Sninca*, Vol. 25, (2009), pp. 23-36; also 46th AIAA Aerospace Sciences Meeting and Exhibit, 7-10 January 2008, Reno, Nevada, Paper No. AIAA 2008-583.

14. Shyy, W., Trizila, P., Kang, C., and Aono, H. “Can Tip Vortices Enhance Lift of a Flapping Wing?” *AIAA J*ournal, Vol. 47, (2009), pp. 289-293.

15. Ol, M., Bernal, L., Kang, C.-K., and Shyy, W., “Shallow and Deep Dynamic Stall for Flapping Low Reynolds Number Airfoils,” *Experiments in Fluids*, Vol. 46, (2009), pp. 883-901.

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26. R.D. Love and R. Lind, ``Time-Frequency Analysis of Aeroelastic Deflections of Flapping Wings," *International Journal of Micro Air Vehicles*, Vol. 3, No. 2, June 2011, pp. 89-100.

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